APPENDIX XA:

CYCLIC TRIAXIAL TESTS

1. PRINCIPLES OF CYCLIC TRIAXIAL TESTING. The stress-controlled cyclic triaxial test is used to evaluate the liquefaction potential and strength of a soil under shear stresses representative of those induced by an earthquake. For horizontal soil deposits, the triaxial specimen is consolidated isotropically, and the cyclic shear stresses generated by an earthquake are simulated in the laboratory by cycling shear stresses along the 45-deg plane of a triaxial compression specimen under undrained conditions. For sloping ground surfaces, the triaxial specimen is consolidated anisotropically. Hence, the test is comparable to an R test with pore pressure measurements (see Appendix X, TRIAXIAL COMPRESSION TESTS) with the notable exception that the load is cyclically applied to the specimen such that the specimen is subjected to alternating cycles of vertical compression and extension about some ambient stress state, which produce corresponding cyclic shear stresses on the 45-deg plane, as illustrated in Figure 1.† Cyclic shear stresses in the test on anisotropically consolidated specimens are depicted in Figure 2.†† Thus, the major difference between cyclic triaxial and conventional triaxial equipment is a rigid fixed connection between the specimen cap and the loading piston.

The consequence of cyclic loading under undrained conditions is generally an increase in the pore water pressure, which causes the

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† M. L. Silver, "Laboratory Triaxial Testing Procedures to Determine the Cyclic Strength of Soils," Report No. NUREG-31, 1976, U. S. Nuclear Regulatory Commission, Washington, D. C.

†† M. L. Silver et al., "Cyclic Triaxial Strength of Standard Test Sand," Journal of Geotechnical Engineering, ASCE, Vol 102, GT5, May 1976.

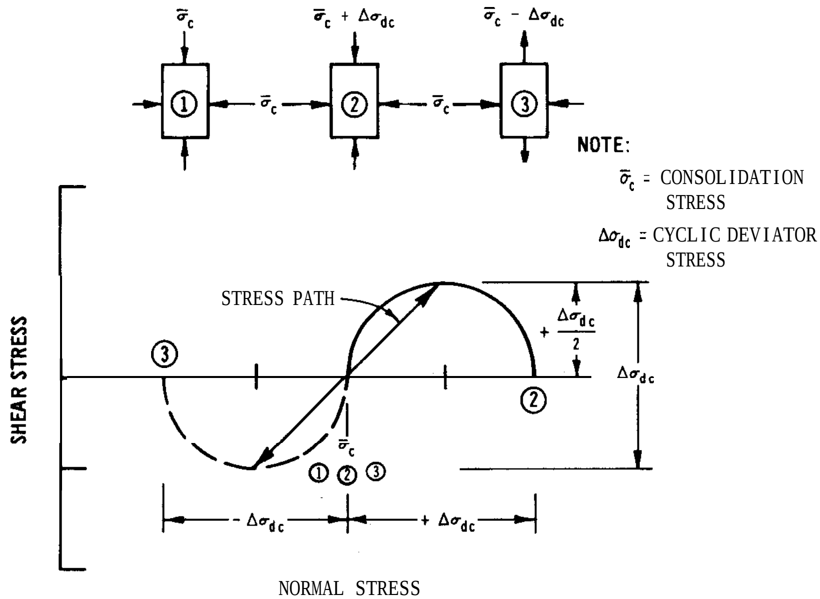

Figure 1. Mohr's circle of total stress representation for a cyclic triaxial strength test for an isotropically consolidated specimen (after Silver, 1976)

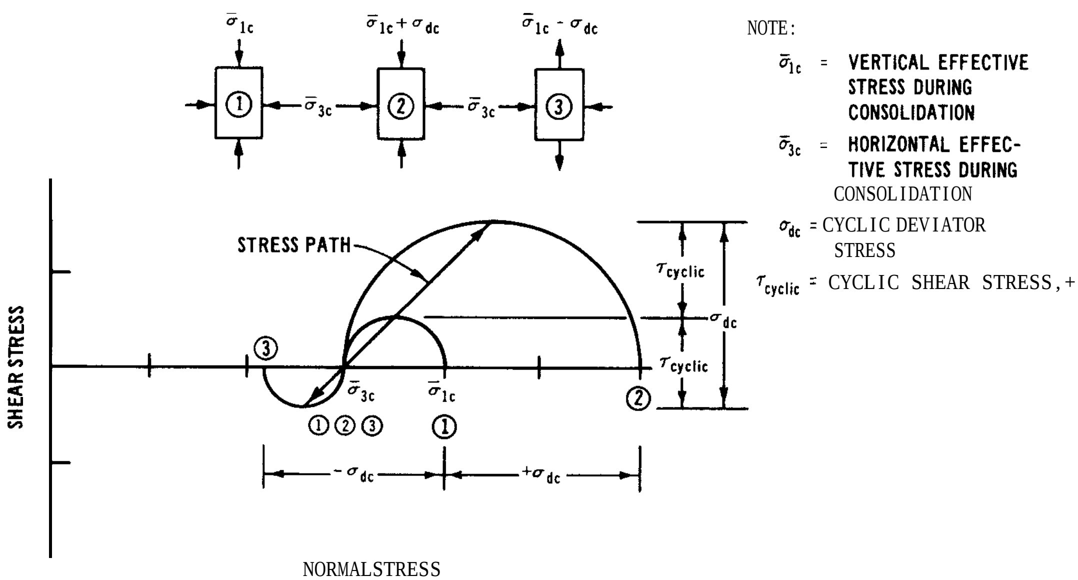

Figure 2. Mohr's circle of total stress representation for a cyclic triaxial test for an anisotropically consolidated specimen (after Silver et al., 1976)

effective stress to decrease and the cyclic deformations of the specimen to increase. In this test, initial liquefaction is defined to occur when the pore water pressure first equals the confining pressure, i.e., a condition where the effective stress is zero, with failure defined in terms of a limiting cyclic strain, generally either 5 or 10 percent from peak to peak. Peak-to-peak strain is usually referred to as double amplitude strain and is the total strain that the specimen undergoes on consecutive peaks of the strain-time trace. For isotropically consolidated specimens, these strains will be alternatively compressional and extensional; however, in the case of anisotropically consolidated specimens, these strains may be alternative compression-extension or permanent compression strain only.

The applied cyclic axial stress, $\sigma_1 - \sigma_3$ or P/A (see Fig. 1 of Appendix X, TRIAXIAL COMPRESSION TESTS), is termed the cyclic deviator stress, σ_{dc}, which is alternatively positive and negative about some ambient stress state. For isotropically consolidated specimens, test results are expressed in terms of the cyclic stress ratio, $\sigma_{dc}/2\sigma_{3c}$, which is the cyclic shear stress, $\sigma_{dc}/2$, normalized by the confining pressure σ_{3c}. For anisotropically consolidated specimens, test results may be expressed in terms $\tau_{cyclic}/\sigma_{fc}$, where τ_{cyclic} is the cyclic shear stress on the failure plane $(45^{\circ} + \phi'/2)$ and σ_{fc} is the normal stress on this plane during consolidation. The value of ϕ' can be estimated or determined from static tests. Research† has shown that the cyclic strength depends on density, confining

† J. P. Mulilis, R. C. Horz, and F. C. Townsend, "The Effect of Cyclic Triaxial Testing Techniques on the Liquefaction Behavior of Monterey No. 0 Sand," Miscellaneous Paper MP S-76-6, Apr 1976, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

F. C. Townsend, "A Review of Factors Affecting Cyclic Triaxial Tests," Dynamic Geotechnical Testing, ASTM STP 654, Jun 1977.

pressure, applied cyclic shear stress, stress history, specimen preparation procedure, and uniformity and shape of cyclic wave form; hence, close attention must be given to testing details and equipment.

2. SPECIMENS. In most cases, only high-quality undisturbed samples should be used for testing since sand fabric (particle orientation) has a considerable effect on cyclic strength. Presently, no techniques are available for duplication of the in situ fabric by laboratory reconstitution. If there is an insufficient number of undisturbed specimens available for a testing program, then correlations between undisturbed and reconstituted specimens are necessary to provide data over the entire range of conditions desired.

3. APPARATUS. All the equipment listed in Appendix X, TRIAXIAL COMPRESSION TESTS, for performing triaxial compression R tests with pore pressure measurements, is required for cyclic triaxial tests in addition to the following special equipment: (1) cyclic loading equipment, (2) electronic transducers and high-speed recorders for data acquisition, and (3) provisions for fixing the specimen cap to the loading piston for the extension portion of the loading cycle.

a. Loading Devices. Dynamic loading equipment used for stress-controlled cyclic triaxial tests must be capable of applying a uniform sinusoidal load at a frequency of 1 Hz or greater. The equipment may be either (1) a closed-loop electrohydraulic system or (2) a pneumatic system.† Both systems basically consist of a pressurized fluid (oil or air) whose pressure into a loading actuator is varied by a servovalve or regulator commanded by a control unit. The system should be capable of maintaining the cyclic deviator load constant throughout the test, i.e., must provide sufficient hydraulic oil or air to permit the loading piston to follow the sudden and rapid specimen deformation at

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† C. K. Chan and J. P. Mulilis, "A Pneumatic Sinusoidal Loading System," Journal of Geotechnical Engineering, ASCE, Vol 102, No. GT3, Mar 1976.

liquefaction. The loading device must maintain uniform cyclic peak loadings throughout the test. Unsymmetrical compression-extension load peaks, nonuniformity of pulse duration, "ringing," or overshoot must not exceed tolerances illustrated in Figure 3.† In these cases, differences in peak compressive and extension loads or durations greater than 10 percent are unacceptable. Both "ringing" and overshoot can induce abnormally rapid pore pressure rises affecting specimen failure.

A problem common to most cyclic loading equipment is the reduction in cyclic load at the onset of large specimen deformation. For the test to be meaningful, the load must be symmetrical in extension and compression up to peak-to-peak strains of 20 percent; and the peak-to-peak load should not decrease by more than 20 percent from the initially applied values until the specimen peak-to-peak strains exceed 10 percent. The equipment must also be able to apply the cyclic load about an initial static load on the loading piston. This static load counteracts the uplift pressure, which results, from the chamber pressure acting on the reduced area of the specimen cap because of the fixed loading piston connection. Further, in the case of anisotropically consolidated specimens, the static load applies some of the consolidation stress.

b. Specimen Cap. The specimen cap should be of a lightweight noncorrosive material equipped with porous metal or porous stone inserts and drainage connections. The cap can be similar to those in paragraph 3c of Appendix X, TRIAXIAL COMPRESSION TESTS, except (1) provisions for fixing the loading piston rigidly to the cap must be provided and (2) specimen diameter should be 2.8 in. or larger. The most common connection is simply straight threads backed by a shoulder on the piston, which tightens up against the loading piston.

c. Triaxial Compression Chamber. The triaxial compression

† Silver, op. cit.

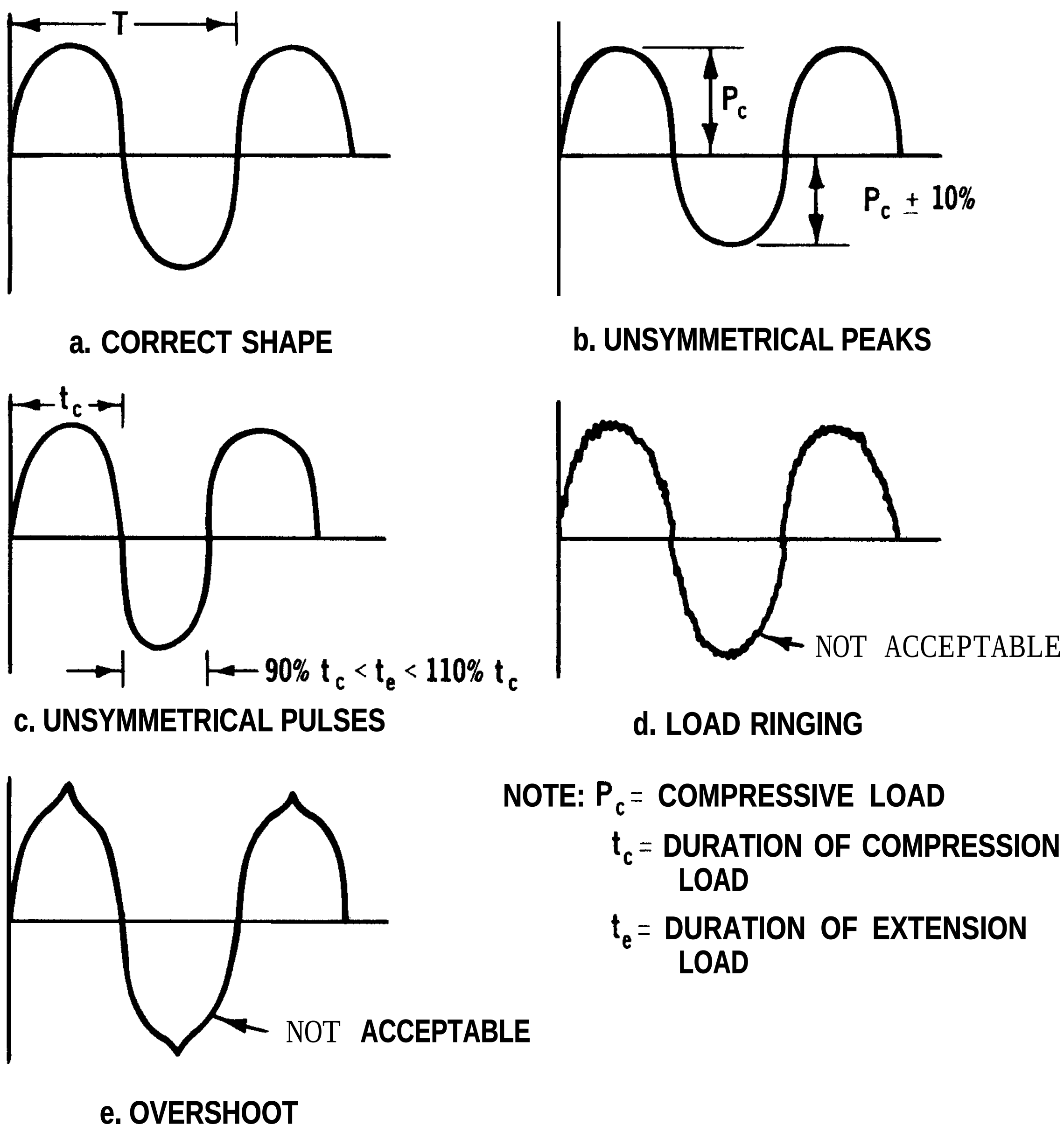


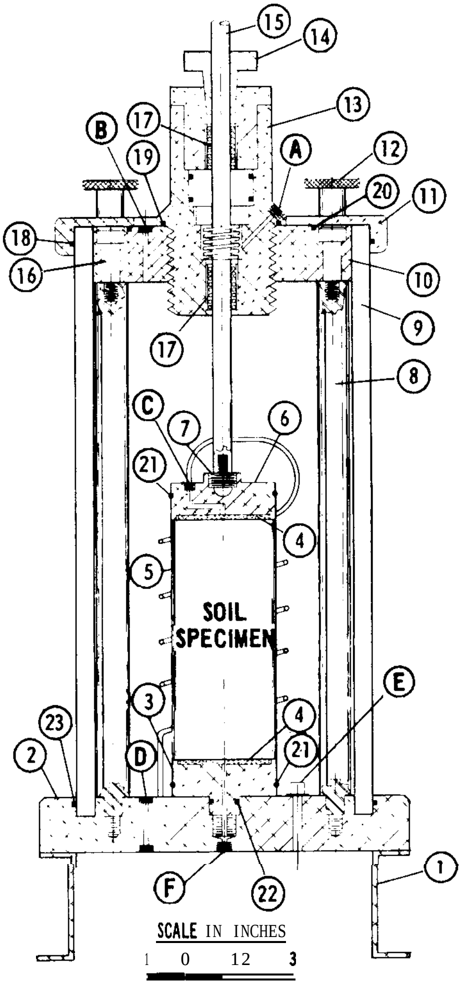
Figure 3. Examples of acceptable and unacceptable loading wave forms for cyclic triaxial strength tests (after Silver, 1976)

chamber consists of a headplate and a baseplate separated by a transparent plastic pressure cylinder. A recent design of a triaxial compression chamber used for cyclic triaxial testing 2.8-in.-diameter specimens is shown in Figure 4. Essential features of this preferred design, compared with that illustrated in paragraph 3b of Appendix X, TRIAXIAL COMPRESSION TESTS, are (1) internal tie-rods and external plastic chamber and (2) a hydrostatic seal with linear ball bushings. The internal tie-rods and external plastic chamber facilitate specimen cap alignment, loading piston to loading machine alignment, and connection of the loading piston to the specimen. Several designs of hydrostatic seal have proven effective.† All incorporate a close tolerance floating sleeve, which allows air to leak between the sleeve and loading piston, eliminating metal-to-metal contact between loading piston and cell and minimizing the speed and pressure-dependent friction inherent in O-rings and bushings.

The maximum acceptable piston friction without applying load corrections is ±2 percent of the maximum cyclic load. Piston friction values can be evaluated by calibration performed by (1) assembling the entire triaxial chamber without a specimen, (2) connecting the chamber to the loading equipment, and (3) recording the load cell output for the complete range of loading piston displacements for the chamber pressures that will be used.

d. Loading Piston to Loading Equipment Connection. The ideal loading piston to loading equipment connector is one that (1) is easy to install; (2) does not slip under cyclic load or vibration; (3) does not twist the specimen during connection; and (4) eliminates the effects of any eccentricity between the line of action of the loading equipment and loading piston. Figure 5 presents three examples of successful connectors: the union nut, split nut, and spherical clamp.

† C. K. Chan, "Low Friction Seal System," Journal of Geotechnical Engineering Division, ASCE, Vol 101, GT9, Sep 1975.



A. HYDROSTATIC SEAL AIR SUPPLY PORT
B. VENT
C. TOP DRAINAGE PORT
D. CHAMBER FLUID DRAIN
E. TRANSDUCER CABLE CONNECTOR
F. BOTTOM DRAINAGE PORT

PART NO.	NAME	MATERIAL	QUANTITY
1	CHAMBER FOOT	ALUMINUM CHANNEL	2
2	CHAMBER BASE	ALUMINUM PLATE	1
3	SPECIMEN BASE	ALUMINUM	1
4	POROUS PLATE	STAINLESS STEEL	2
5	SPECIMEN MEMBRANE	RUBBER	1
6	SPECIMEN CAP	ALUMINUM	1
7	SPECIMEN CAP CONNECTOR	BRASS	1
8	BEARING SUPPORT ROD	STAINLESS STEEL	2
9	CYLINDER	CLEAR ACRYLIC	1
10	CHAMBER CAP	ALUMINUM	1
11	CYLINDER SEALING RING	ALUMINUM	1
12	LOCKING KNOBS	STEEL	3
13	AIR BEARING ASSEMBLY	ALUMINUM	1
14	PISTON LOCK	BRASS	1
15	LOADING PISTON	STAINLESS STEEL	1
16	SHOULDER SCREW	STEEL	2
17	BALL BUSHING	STAINLESS STEEL	2
18	O-RING	RUBBER	1
19	O-RING	RUBBER	1
20	O-RING	RUBBER	1
21	O-RING	RUBBER	2
22	O-Ring	RUBBER	1
23	O-RING	RUBBER	1

Figure 4. Triaxial compression chamber used for cyclic triaxial tests (working drawings for design shown available from Soil Mechanics Division, Geotechnical Laboratory, U. S. Army Engineer Waterways Experiment Station)

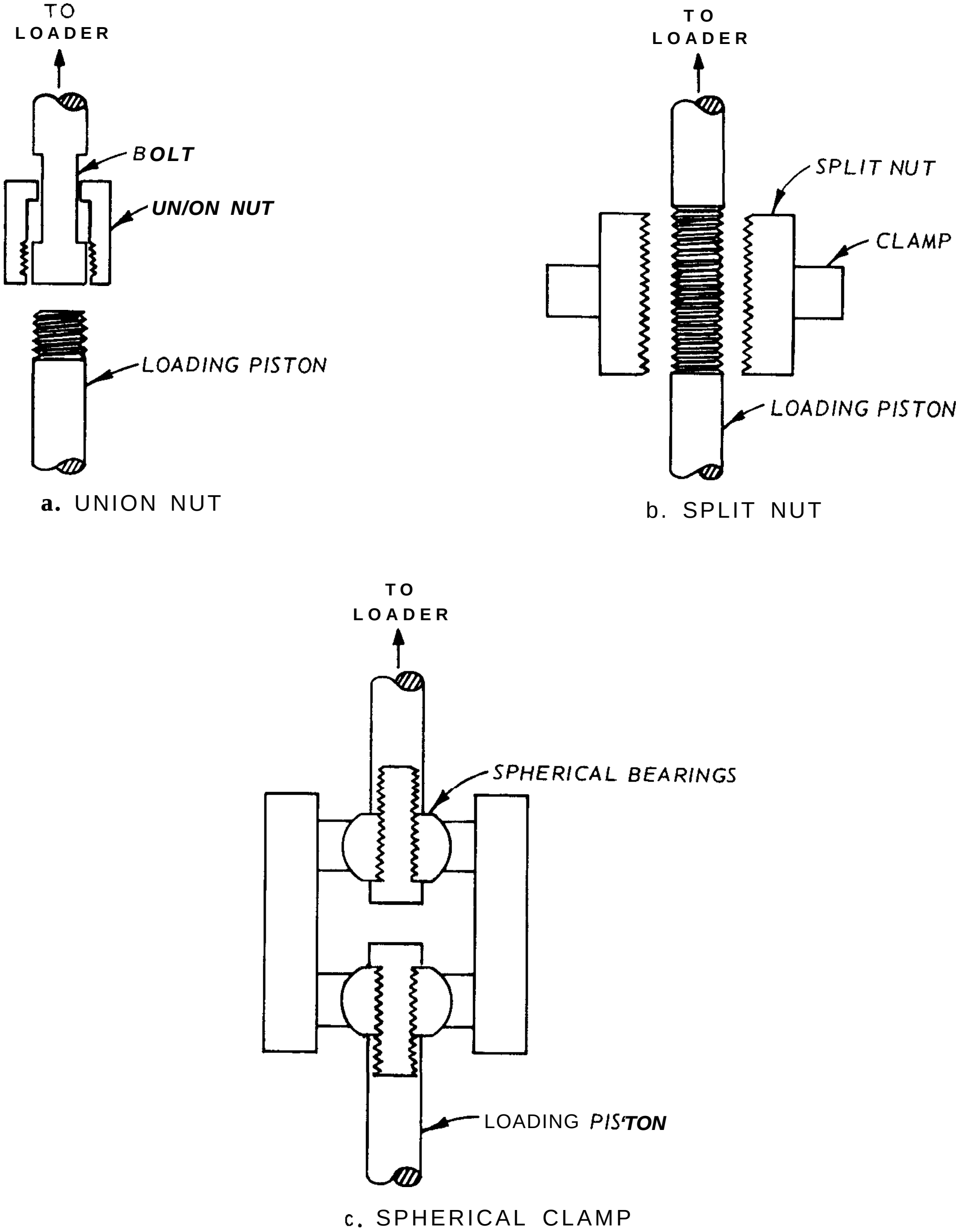


Figure 5. Examples of successful connections between triaxial cell loading piston and cyclic loading actuator (after Silver, 1976)

e. Recording Equipment. Specimen behavior in stress-controlled cyclic triaxial tests is evaluated from continuous time records of applied load, specimen deformation, and change in pore water pressure. Commonly, these parameters are recorded on a multichannel strip-chart recorder, as illustrated in Figure 6. Analog to digital data acquisition systems may be used provided that data can be converted later into a convenient form for data analysis and interpretation. Fast recording system response is essential if accurate specimen performance is to be monitored when failure conditions are approached. It is recommended that the response characteristics in Table 1 be satisfied.

For analog strip-chart recording equipment, the magnitude of the load, deformation, and pore water pressure (chamber pressure recording is optional) recorder trace must be of sufficient amplitude and time resolution to enable accurate data reduction. Resolution of each variable should be better than 2 percent of the maximum value being measured. To take advantage of recorder accuracy and for subsequent data analysis, a recorder speed of 2-4 cycles per in. of recording paper is acceptable. The clarity of the trace with respect to the background should provide sufficient contrast and minimum trace width, so that the minimum resolution of 2 percent of the maximum value of the recorded parameter is maintained, and the trace may be included in reports.

f. Measurement Transducers. Load, displacement, and pore water pressure transducers are required to monitor specimen behavior during stress-controlled cyclic triaxial tests; provisions for monitoring the chamber pressure are optional. Each of these transducers must have the required capacity to ensure that the full range of specimen characteristics are monitored; at the same time, they must have the required sensitivity to ensure that small changes in specimen behavior are properly measured and recorded.

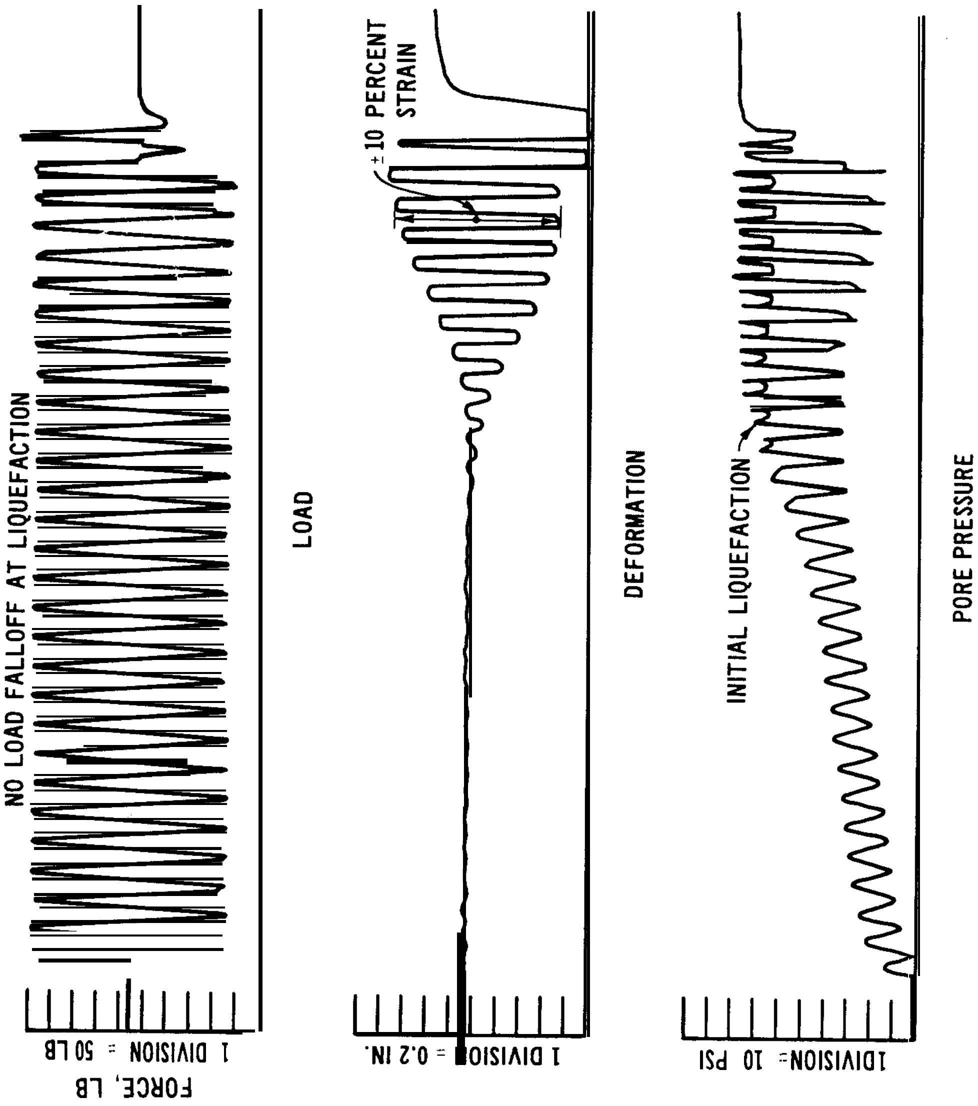


Figure 6. Analog recordings of load, deformation, and pore pressure during cyclic triaxial test

Table 1

Data Acquisition

Minimum Response Characteristics for Cyclic Triaxial Strength Tests

1. Analog Recorders

Recording Speeds: 0.5 to 50 cm/sec (0.2 to 20 in./sec)

System Accuracy (include linearity and hysteresis): 0.5%[1]

Frequency Response: 100 Hz

2. Measurement Transducers

	Load Cell	Displacement Transducer (LVDT)[2]	Pore Pressure
Minimum sensitivity, mv/v	2	0.2 mv/0.025 mm/v (AC LVDT) 5 mv/0.025 mm/v (DC LVDT)	2
Nonlinearity, % full scale	± 0.25	± 0.25	± 0.5
Hysteresis, % full scale	± 0.25	0.0	± 0.5
Repeatability, % full scale	± 0.10	± 0.04	± 0.5
Thermal effects on zero shift or sensitivity, % of full scale/°C(°F)	± 0.005 (± 0.025)	--	± 0.02 (± 0.01)
Maximum deflection at full rated value in mm (in.)	0.425 (0.005)		
Volume change characteristics (cu in./psi)			1.0×10^{-4}

Note: (1) System frequency response, sensitivity, and linearity are functions of the electronic system interfacing, the performance of the signal conditioning system used, and other factors. It is therefore a necessity to check and calibrate the above parameters as a total system and not on a component basis.

(2) LVDT's, unlike strain gauges, cannot be supplied with meaningful calibration data. System sensitivity is a function of excitation frequency, cable loading, amplifier phase characteristics, and other factors. It is necessary to calibrate each LVDT-cable-instrument system after installation, using a known input standard.

(1) Load transducers. · The total load capacity of the load transducer (load cell) should be of the proper order of magnitude with respect to the maximum total loads to be applied to the test specimen. Generally its capacity should be no greater than five times the total maximum load applied to the test specimen to ensure that the necessary measurement accuracy is achieved. The minimum performance characteristics of the load cell are presented in Table 1.

A rigid load cell is required to avoid resonance problems that can develop with closed-loop electrohydraulic loading systems.

Miniature lightweight load cells are used to prevent inertia effects during cycling. The load cell is normally placed outside the triaxial chamber. If the load cell is located inside the triaxial chamber, special provisions must be provided to either pressurize the load cell or normalize the effects of cell pressure to ensure that load readings are not affected by the cell pressure. In all cases, the response and performance of a load cell located inside the pressure chamber must be documented.

(2) Deformation measurement. The stress-controlled cyclic triaxial test requires a deformation transducer with a high resolution and small range during the initial portion of the test and less resolution but large range during the final portion of the test. The linear variable differential transformer (LVDT) is generally considered to be the most suitable deformation transducer for the test, and its minimum specifications will be discussed. However, other displacement measuring devices, such as eddy current sensors or optical methods, may be used if they meet the required performance criteria. Potentiometer type deformation transducers are not recommended because they are easily damaged if their maximum travel is exceeded.

The displacement transducer must have a range of at least 20-30 percent of specimen height but should not exceed 60 percent of specimen height. The specifications for this transducer, representing levels on nonlinearity, hysteresis, and repeatability, are also presented in Table 1.

Accurate deformation measurements in dynamic triaxial tests require that the LVDT be properly mounted to avoid excessive mechanical system compression between the load frame, the triaxial cell, the load cell, and the loading piston. Thus, it is recommended that the LVDT be located either on the actuator rod or on the loading piston attached to the test specimen.

(3) Pore water pressure measurements. Pore water pressures may be individually measured in the drainage line(s) leading to either (or both) the specimen cap or base. However, more reliable measurements may be achieved if pore water pressure is measured at both the cap and base simultaneously by having a connection in the drainage lines between the specimen and the pressure transducer. The use of a differential pressure transducer will facilitate data reduction.

A rigid pore water pressure measuring system is required. To achieve reliable measurements, it is recommended that pore water pressure transducer volume change not exceed 1×10^{-4} cu in. per psi and that the transducers have the sensitivity and performance characteristics summarized in Table 1. Moreover, the rigidity of all the assembled components of the pore water pressure measurement system should not exceed 1×10^{-4} cu in. per psi. In general, stiff, small-diameter tubing of metal or Saran, short-tubing runs, and high-quality ball valves are required to meet this specification. In all cases, the rigidity of the entire pore water pressure system, including the transducer, must be ascertained and documented. Methods for measuring the rigidity of the entire pore water pressure system are presented by Wissa (1969)† and Bishop and Henkel (1962).††

g. Saturation Equipment. The apparatus for back-pressure saturation described in Appendix X is adequate provided the optional vacuum source with a vacuum regulator is included in the setup. The vacuum source must have a means of regulation for those instances where the effective consolidation stress to be applied to specimens is less than the pressure difference suppliable by the vacuum. Carbon dioxide gas (CO_2) has been found very helpful in obtaining complete saturation in those instances where a full vacuum cannot be applied. The CO_2 is permitted to seep up through the specimen prior to seepage saturation.

h. Tamping Rod for Moist Tamping Specimen Preparation. (Optional) The "standard" moist tamping specimen preparation procedure uses a tamping foot, whose diameter is one-half that of the specimen. Figure 7 shows a sketch of a tamping foot for a 2.8-in.-diameter specimen. The tamping rod consists of a 3/4-in.-diameter steel rod 12 in. long with a 1.4-in.-diameter steel tamping foot attached to the end.

4. TESTING PROCEDURES. Specimen preparation, back-pressure saturation, and consolidation procedures specified in paragraphs 4b and 7b(1) through 7b(7), Appendix X, TRIAXIAL COMPRESSION TESTS, are adequate and pertinent. However, preferred techniques for handling undisturbed samples of cohesionless soils, preparing remolded specimens for a standard test calibration procedure,* and anisotropic consolidation are as follows:

a. Reconstituted Specimen Preparation (Moist Tamping). The procedure is as follows:

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† A. E. Z. Wissa, "Pore Pressure Measurement in Saturated Stiff Soils," Journal of Soil Mechanics and Foundations Engineering, ASCE, Vol 95, No. SM4, July 1969.

†† A. W. Bishop and D. J. Henkel, The Measurement of Soil Properties in the Triaxial Test, 2nd ed., London, Edward Arnold Ltd., 1962.

* Mulilis et al., op. cit.; and Silver, op. cit.

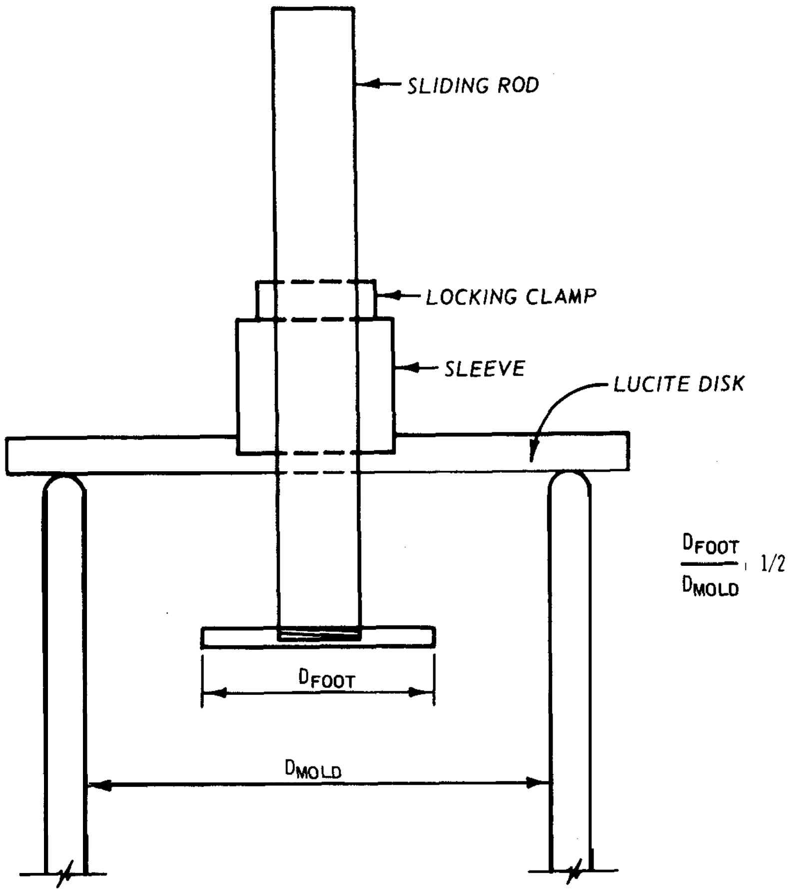

Figure 7. Tamping rod

(1) Adjust the water content of the material, so, that the initial degree of saturation of the compacted material will be between 20 and 70 percent.

(2) Place the forming jacket, with membrane inside, over the specimen base of the triaxial compression chamber.

(3) Evacuate the air between the membrane and inside face of the forming jacket, so that the membrane is taut and flush against the face.

(4) Determine the inside diameter and height of the mold to within 0.001 in. for 2.8-in.-diameter specimens, and calculate the

volume based on these measurements.

(5) Select the number of layers to be used in the preparation of the specimen. The maximum thickness should not exceed 1.0 in. for specimens having diameters less than 4.0 in.

(6) Starting with the bottom layer, compact each layer to the desired density using the tamping rod. The locking collar on the rod must be adjusted to produce the desired height to within 0.001 in. for each layer. This is 'most easily done by adjusting the travel of the foot for each layer using a set of gage blocks.

(7) A procedure of variable compaction, such as that described in paragraph 4b(4), Appendix X, TRIAXIAL COMPRESSION TESTS, may be used to construct uniform specimens. An alternative and similar procedure consists of building the specimen in equal thickness layers but placing each successive layer in a slightly denser state. For example, an increase of one percentage point of relative density per layer (the top layer placed to the desired average relative density for the entire specimen) has been found satisfactory for medium dense sand.

(8) After the forming jacket is filled to the desired height, place the specimen cap on top of the specimen, pull the membrane end over the cap, and fasten with O-rings. Carefully apply a vacuum to the interior of the specimen while observing the response of the specimen pressure transducer. Adjust the vacuum regulator as necessary to assure that the differential pressure supplied by the vacuum is not greater than the intended effective consolidation stress. A vacuum gage located between the vacuum regulator and valve K (see Fig. 16 of Appendix X) simplifies this procedure by indicating the differential supplied by the vacuum while valve K is still closed. With a vacuum on the interior of the specimen, remove the forming jacket and measure the specimen dimensions.

b. Undisturbed Specimen. Preparation. Sampling, transporting, and testing undisturbed specimens of loose free-draining cohesionless materials so as to minimize disturbance is an extremely difficult task. However, the current practice is as follows:

(1) Obtain samples using a fixed-piston sampler and drilling mud.

(2) Place perforated packers at both ends of the sampling tube and allow the tube to drain in a vertical position. Drainage of the tube should be monitored and, if insufficient, can be aided by the application of a low vacuum, i.e. 5 in. (2.5 psi) of mercury (Hg), to the bottom packer.

(3) After drainage, the sample may be carefully transported to the laboratory, or alternatively frozen in the field using dry ice or liquid nitrogen and transported to the laboratory in a frozen condition. Free-draining samples, which contain no silt or clay layers that would form ice lenses upon freezing, should be transported frozen. It is important to monitor the sample length at all stages (after sampling, after drainage, after freezing, after transportation, and again before testing). Samples should be stored vertically, and storage time at the laboratory minimized to prevent corrosion of the tubes.

(4) (Optional) Keeping the sample frozen, X-ray the tube to observe possible layering of the sample, voids, gravels, etc., in the tube† and to facilitate selection of 7-in. sections for testing.

(5) If a milling machine is available, the tube may be cut lengthwise at two diametrically opposite places, using a rapid feed, and then cut into sections with an electric hacksaw. If a milling machine is not used, the desired section is cut with an electric hacksaw or a tube cutter with stiffening collars. The cut ends of the tube are then cleaned

† W. F. Marcuson III and E. L. Krinitzky, "Dynamic Analysis of Ft. Peck Dam," Technical Report S-76-1, U. S. Army Engineer Waterways Experiment Station, Nov 1976, Vicksburg, Miss.

of burrs, and the specimen is pushed from the tube after having been permitted to thaw slightly.

(6) The ends of the specimen should be trimmed smooth and perpendicular to their length using a mitre box or other trimming device. The specimen is then placed in the triaxial chamber and enclosed in a rubber membrane; then, a small vacuum (always less than $\bar{\sigma}_3$) is applied to hold it firmly while thawing. It is usually necessary to place the sample in a freezer at times during the cutting and trimming process to ensure that the specimen remains frozen until enclosed in the membrane.

(7) Dimensions of the specimen are taken to calculate the initial volume. If frozen, measurements are checked after the specimen has thawed. There should be no significant volume change; otherwise, freezing or transportation have caused sample disturbance.

c. Specimen Measurement. Inasmuch as density greatly influences the cyclic triaxial strength, it is imperative that accurate density determinations and volume change measurements be made during saturation and consolidation. For this reason, diameter measurements using a circumferential tape† to the nearest 0.001 in., height measurements to the nearest 0.01 in. at four locations, and weights to the nearest 0.1 g are recommended for 2.8-in.-diameter specimens.

d. Saturation. Saturation generally includes a stage during which water is allowed to seep into the specimen while its interior is under vacuum, followed by back pressuring to drive the remaining air in the specimen into solution with the pore water. A procedure found to be effective is as follows:

(1) After assembling the triaxial chamber, apply a small chamber pressure, 1-3 psi, to the specimen, and increase the vacuum to the interior, noting that any vacuum on the interior of the specimen

† Commercially available from PI Tape, Box 398, Lemon Grove, Calif. 92045.

contributes to the effective stress and that the difference between the vacuum and chamber pressures must not exceed the effective consolidation stress.

(2) After allowing the specimen to remain under vacuum for a period of approximately 5-15 min, permit de-aired water to slowly seep up through the specimen from the bottom. The upward movement of water must be slow enough to minimize entrapment of air pockets. The use of de-aired water further promotes the removal of air by solution. Flushing of water through the specimen should continue until gas bubbles no longer come from the upper drainage line.

(3) After seepage saturation, reduce the vacuum and increase the chamber pressure simultaneously until the specimen is at atmospheric pressure. Back pressure the specimen in steps and evaluate the degree of saturation at appropriate intervals using Skempton's pore pressure parameter B . To do this, close the drainage lines from the specimen, increase the chamber pressure 5 or 10 psi, and adjust the axial load to match the increase in chamber pressure. Observe the pore pressure increase, Au , and calculate B , using the equation:

$$B = \frac{\Delta u}{\Delta \sigma_3}$$

The specimen shall not be considered adequately saturated unless the B value is greater than 0.95.

In some cases, a satisfactory degree of saturation cannot be achieved by ordinary vacuum seepage and back-pressure saturation techniques. This may be due to a weak vacuum source or to the need to keep the vacuum low to prevent prestressing the specimen. In the latter case, it is possible to apply a sufficient vacuum to the chamber so that there is no prestressing of the specimen when a full, i.e. 14.7 psi, vacuum is applied to the interior of the specimen.

In either of the cases where the vacuum is limited, CO_2† can be allowed to slowly seep upward from the bottom of the specimen, while the specimen is being formed or after it has been confined in the triaxial chamber. The CO_2 will displace the air in the specimen and, being much more soluble in water than air, will enable subsequent saturation steps to be carried out successfully.

During saturation, the change in height of the specimen should be measured to the nearest 0.001 in. In addition, during saturation and consolidation, an axial load must be applied to the loading piston, which is screwed into the specimen cap, to compensate for the uplift force on the loading piston. This static load will be expressed as

$$P_s = \sigma_3 A_r - \text{weight of apparatus below the load cell}$$

where

P_s = static load applied to specimen

σ_3 = chamber pressure

A_r = area of the loading piston

e. Consolidation. Isotropic consolidation is defined as

$$K_c = \frac{\bar{\sigma}_{1c}}{\bar{\sigma}_{3c}} = 1$$

where

K_c = consolidation ratio

$\bar{\sigma}_{1c}$ = vertical effective consolidation stress

$\bar{\sigma}_{3c}$ = horizontal effective stress

To consolidate the specimen isotropically, maintain the applied back-pressure constant and increase the chamber pressure until the

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† Mulilis et al., op. cit.

difference between the chamber pressure and the back pressure equals the desired consolidation pressure. An axial load to counterbalance uplift due to increasing the chamber pressure must be applied. This may require incrementally applying the consolidation pressure to provide sufficient time to apply and adjust the counterbalancing uplift load. Changes in specimen height during consolidation should be measured to the nearest 0.001 in., and the change in specimen volume 'to the nearest 0.01 cc. A plot of burette and/or height readings versus logarithm of elapsed time, as shown in Figure 5 of Appendix VIII, CONSOLIDATION TEST, is optional.

Anisotropic consolidation is defined as

$$K_c = \frac{\bar{\sigma}_{1c}}{\bar{\sigma}_{3c}} \neq 1$$

This consolidation condition may be achieved by incrementally increasing the chamber pressure, $\bar{\sigma}_{3c}$, and by increasing the axial load to the required $\bar{\sigma}_{1c}$, plus uplift counterbalancing value, until the final $\bar{\sigma}_{3c}$ value is achieved. As stated previously, changes in specimen height and volume should be measured during consolidation.

Following consolidation, the drainage lines should be closed and the pore water pressure observed for a period of time to verify that no leaks in the membrane or pore water pressure system have occurred. If the time for consolidation exceeds 8 hr, the B value should be redetermined prior to cyclic loading.

f. Cyclic Loading. If it does not already exist, a large air pocket should be formed at the top of the triaxial chamber by draining water from the chamber but leaving sufficient water to cover the top of the specimen. The air pocket is required, so that the large, rapid piston movements in and out of the chamber at the onset of failure do not create chamber pressure fluctuations. Compressed air instead of water may be used as the confining fluid provided saturation and consolidation do not exceed 8 hr. The procedure is as follows:

(1) Record test number and specimen identification on recorder trace.

(2) Zero the recorder and transducer outputs, and record calibration steps and scale factors.

(3) Close valve F (D should have been already closed) as shown in Figure 16 of Appendix X, TRIAXIAL COMPRESSION TESTS.

(4) Record the consolidation pressure, $\bar{\sigma}_c$, and estimate the magnitude of cyclic load to be applied for the desired stress ratio, SR , with the equation:

$$P_c = 2 \times \bar{\sigma}_{3c} \times SR \times A_c$$

where

P_c = estimated cyclic load to be applied to the specimen, lb
$\bar{\sigma}_{3c}$ = consolidation pressure (chamber pressure-back pressure), psi
SR = desired stress ratio
A_c = area of specimen after consolidation, sq in.

(5) Initiate cyclic loading with the first half cycle in compression using a 1- to 2-Hz sinusoidal load form. During cyclic loading, the chamber pressure is maintained constant, and the axial load, axial deformation, and change in pore water pressure (recording of chamber pressure is optional) are recorded with time. The load is cycled until either (a) the cyclic double amplitude strain exceeds 20 percent: (b) 500-load cycles or the maximum number required in the program is surpassed; (c) “necking” of the specimen is observed; or (d) the load wave form deteriorates beyond acceptable values.

In cases of anisotropic consolidation, where

$$\frac{\sigma_{dc}}{2\bar{\sigma}_{3c}} < \frac{K_c - 1}{2}$$

there will be no reversal in the direction of shear stress application, and the net axial stress will always be the major principal stress. For these conditions, the pore pressure does not usually increase sufficiently to produce initial liquefaction, rather the specimen tends to deform progressively. Conversely, where

$$\frac{\sigma_{dc}}{2\bar{\sigma}_{3c}} > \frac{K_c - 1}{2}$$

there will be a stress reversal and conditions of initial liquefaction usually occur.

g. Specimen Removal. Following cyclic testing, the specimen should be carefully removed from the triaxial cell in order that no particles are lost, then dried and weighed for dry unit weight calculations.

5. COMPUTATIONS. a. From the initial specimen data recorded on Plate XA-1, compute the initial water content, initial void ratio, initial dry density, and if required, the initial relative density, using equations presented in Appendixes I, WATER CONTENT - GENERAL, and II, UNIT WEIGHTS, VOID RATIO, POROSITY, AND DEGREE OF SATURATION.

b. From saturation and consolidation data, compute the values of Skempton's pore pressure parameter B, and record any specimen dimension changes during saturation, the static piston loads required to counterbalance uplift pressures, and the magnitude of applied back pressure (Plate XA-1 (Cont'd)).

c. From specimen dimension and volume changes during saturation and consolidation, compute the height, area, and dry density of the specimen after consolidation, using the following formulas:

$$A_s = \frac{A_o}{H_o}(H_o - 2\Delta H_s)$$

$$V_s = A_s(H_o - \Delta H_s)$$

$$H_c = H_0 - \Delta H_s - \Delta H_c$$

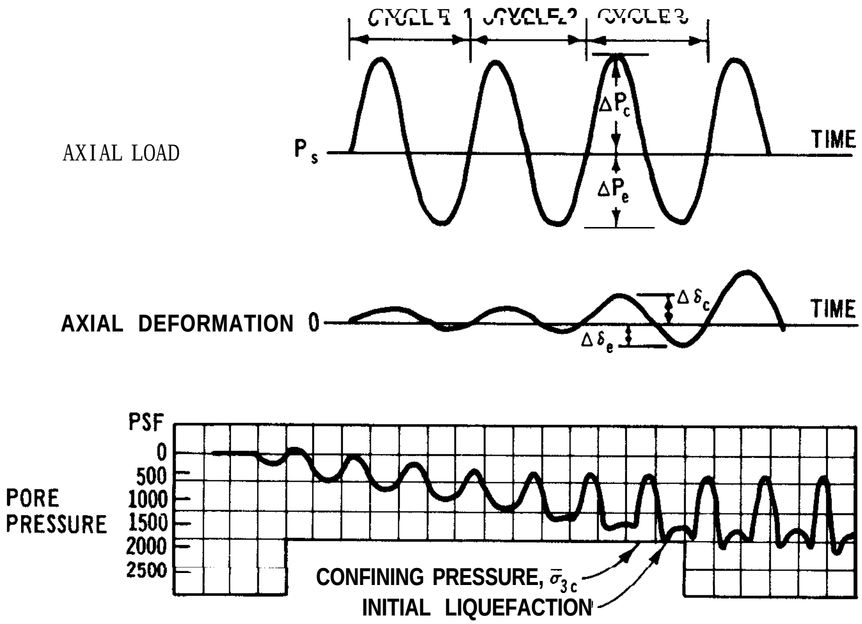
$$A_c = \frac{V_s - \Delta V_w}{H_c}$$

$$\gamma_{dc} = \frac{W_s}{A_c H_c} \times 62.4$$

where

A_s = area of specimen after saturation, sq cm
A_o = initial area of specimen, sq cm
H_o = initial height of specimen, cm
ΔH_s = change in height during saturation, cm
V_s = volume of specimen after saturation, cc
H_c = height of specimen after consolidation, cm
ΔH_c = change in height during consolidation, cm
A_c = area of specimen after consolidation, sq cm
ΔV_w = burette change during consolidation, cc
γ_{dc} = dry density after consolidation, pcf
W_s = weight of solids, g

d. After testing, use the data from the strip chart recorder and the relationships and definitions presented in Figure 8 to determine the cyclic stress, stress ratio, double amplitude strain (all based on consolidated specimen dimensions), and the induced pore water pressure; record these data on Plate XA-1. The number of cycles required to



DEFINITION OF CYCLIC STRESS, STRESS RATIO AND DOUBLE AMPLITUDE STRAIN

$$\text{CYCLIC STRESS, } \pm\sigma_{dc} = \frac{\Delta P_c + \Delta P_e}{2A_c}$$

$$\text{CYCLIC STRESS RATIO, SR} = \frac{\pm\sigma_{dc}}{2\bar{\sigma}_{3c}}$$

$$\text{DOUBLE AMPLITUDE STRAIN, } \epsilon_{da}, \% = \frac{\Delta\delta_c + \Delta\delta_e}{H_c} \times 100$$

WHERE:

ΔP_c = PEAK CYCLIC LOAD IN COMPRESSION

ΔP_e = PEAK CYCLIC LOAD IN EXTENSION

$\pm\sigma_{dc}$ = CYCLIC DEVIATOR STRESS

$\pm\sigma_{dc}/2$ = CYCLIC SHEAR STRESS

δ_c = CYCLIC DEFORMATION IN COMPRESSION

δ_e = CYCLIC DEFORMATION IN EXTENSION

ϵ_{da} = DOUBLE AMPLITUDE AXIAL STRAIN, PERCENT

A_c, H_c = AREA AND HEIGHT AFTER CONSOLIDATION, RESPECTIVELY

Figure 8. Definitions and equations for computing cyclic stress, stress ratio, and double amplitude strain

achieve initial liquefaction (defined as 100 percent pore pressure response) and various strain amplitudes are also recorded in Plate XA-2.

The uniformity of the load trace into the failure state should be evaluated to ensure that the load uniformity criteria (see paragraph 3a) are achieved.

6. PRESENTATION OF RESULTS. a. Results of individual tests on specimens, which have been isotropically consolidated, are generally presented by plotting various percent (e.g. 5, 10, and 20) double amplitude strain versus number of cycles required to reach those strains. Since anisotropically consolidated specimens often reach failure strains in compression only, the various percentages of zero-to-peak compressive strain can be plotted versus number of cycles to reach those strains. In addition, pore pressure increase, $\Delta u / \bar{\sigma}_{3c}$, versus number of cycles to reach those percentages of increase (e.g. 25, 50, 75, and 100) can be plotted; the number of cycles to reach the given increase is denoted as N_{25i}, N_{50i}, N_{75i}, and N_i, respectively.

b. In analyzing the results of a series of isotropically consolidated cyclic triaxial strength tests, the number of cycles required to achieve initial liquefaction and various values of double amplitude strain are plotted (see Plate XA-2 and Fig. 9) versus stress ratio, SR, that is defined as

$$SR = \pm \frac{\sigma_{dc}}{2\,\bar{\sigma}_{3c}}$$

In the case of anisotropically consolidated cyclic triaxial strength tests, the definition of stress ratio is not appropriate, as $\bar{\sigma}_{3c}$ does not represent the total consolidation stress. Hence only $\pm\sigma_{dc}$ which is the cyclic deviator stress, versus log number of cycles for various values of strain (double amplitude and/or zero to peak compressional) are plotted on Plate XA-2.

For test series involving both anisotropically and isotropically

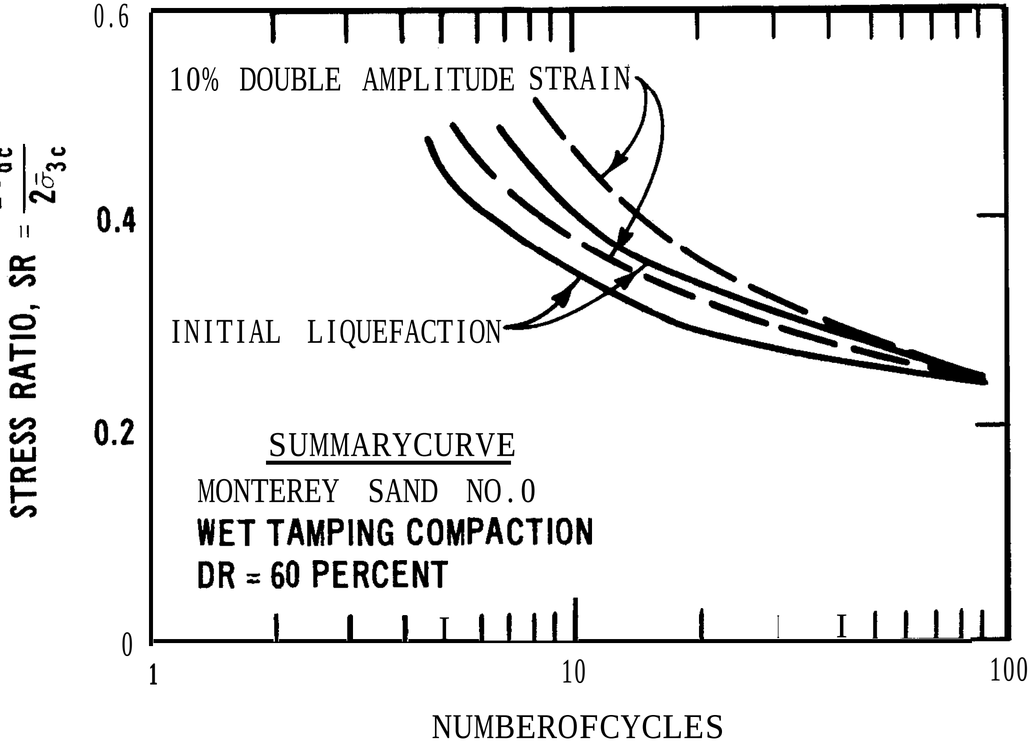
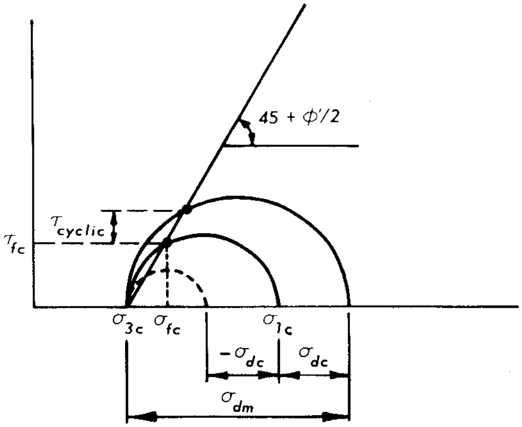


Figure 9. Range of cyclic triaxial strength values for initial liquefaction and 10 percent double amplitude strain

consolidated cyclic triaxial specimens, a summary figure of cyclic shear stress, τ_{cyclic}, on the failure plane ($45^{\circ} + \phi'/2$), required to produce a specified strain in a specified number of cycles versus the effective normal stress on the failure plane after consolidation, σ_{fc}, for various K_c ratios, as shown in Figure 10, is desirable. The ϕ' used in establishing the failure plane can be derived from static tests or may be assumed at some representative value.

c. To estimate the cyclic triaxial strength of undisturbed specimens, a density correction to account for differences between in situ densities and specimen density after consolidation can be made using



τ_{fc} = INITIAL SHEAR STRESS ON POTENTIAL FAILURE SURFACE

$$= \frac{\sigma_{3c}}{2}\,(K_c - 1)\cos\phi'$$

τ_{cyclic} = CYCLIC SHEAR STRESS DEVELOPED ON POTENTIAL FAILURE SURFACE

$$= \frac{\sigma_{dc}}{2}\cos\phi' \text{ OR } \left[\sigma_{dm} - \sigma_{3c}(K_c - 1)\right]\frac{\cos\phi'}{2}$$

σ_{fc} = INITIAL NORMAL STRESS ON POTENTIAL FAILUE SURFACE

$$= \frac{\sigma_{3c}}{2}\left[(K_c + 1) - (K_c - 1)\sin\phi'\right]$$

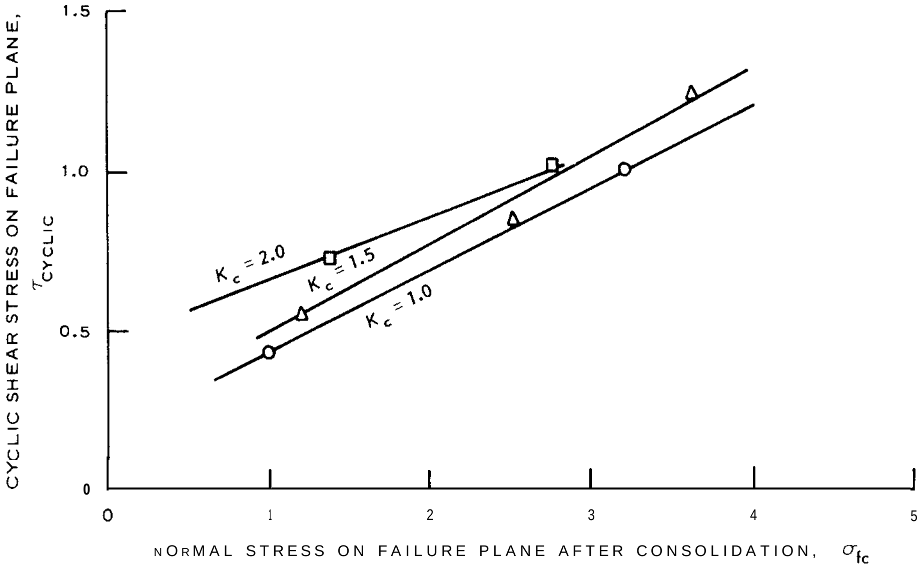


Figure IO. cyclic shear stress on failure plane, τ_{cyclic}, versus normal stress on failure plane after consolidation, σ_{fc}, for 5 percent strain in 5 cycles

the following empirical relationship,† provided D_d (laboratory) is near 50 percent:

$$\frac{\sigma_{dc}}{2\,\sigma'_{o(D_d\ \text{field})}} = \frac{\sigma_{dc}}{2\,\sigma'_{o(D_d\ \text{lab})}} \times \frac{D_d\ \text{field}}{D_d\ \text{lab}}$$

7. CALIBRATION OF EQUIPMENT AND TESTING PROCEDURES. Adherence to apparatus specifications and testing procedures are necessary but does not ensure that the cyclic triaxial test results from one laboratory will be comparable to those of other laboratories. Accordingly, a performance calibration has been developed using a standard test sand, Monterey No. 0,†† and standard test procedures.‡ It is recommended that each laboratory verify its performance by calibration using this standard test sand and techniques as follows:

a. Standard Test Sand - Monterey No. 0. Figure 11 presents the grain-size distribution and pertinent physical properties.

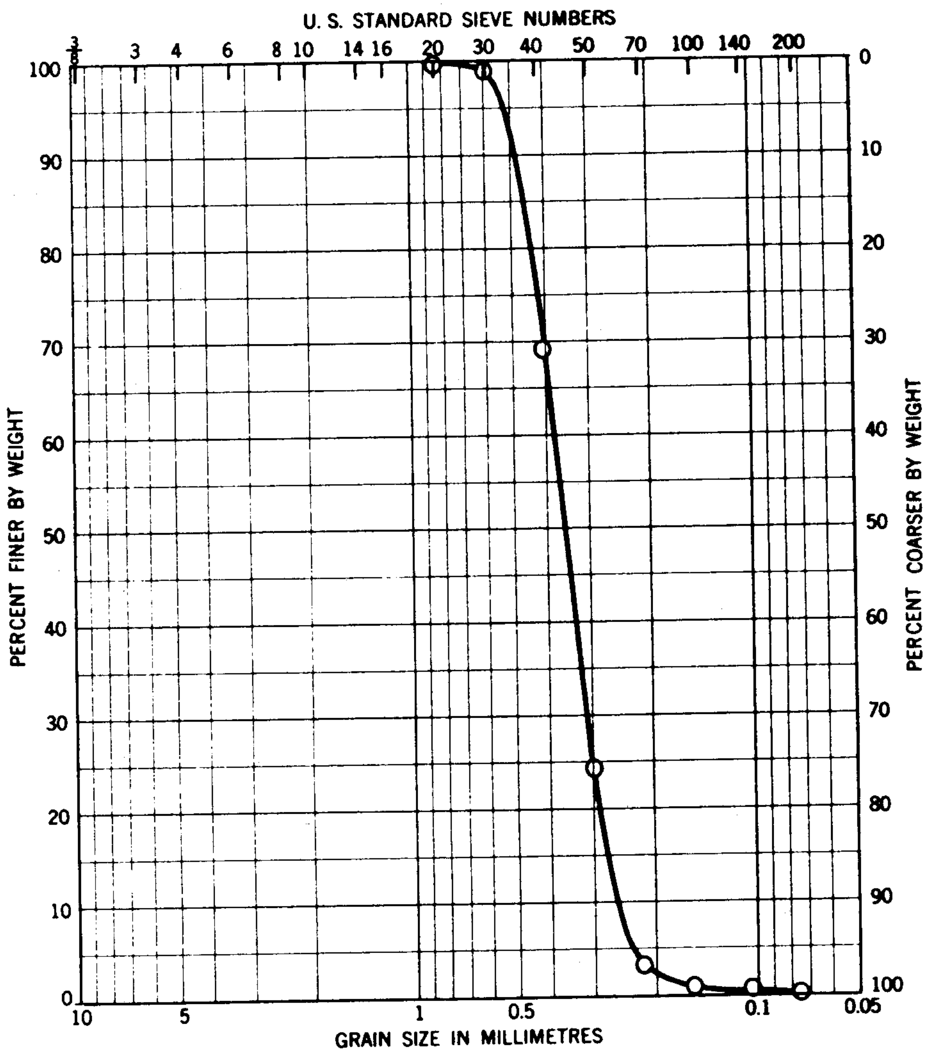
b. Specimen Preparation. Specimens, 2.8 in. in diameter by 6-7 in. high, are to be prepared to an initial density of 98.5 pcf (60 percent relative density) using the moist tamping procedure and moist tamping rod described in paragraphs 3h and 4a.

c. Effective Confining Pressure. The effective confining

† H. B. Seed, and I. M. Idriss, "A Simplified Procedure for Evaluating Soil Liquefaction Potential," Journal of Soil Mechanics and Foundations Engineering, ASCE, Vol 97, No. SM9, Sep 71.

†† Available from Lone Star Company, 9315 San Leandro St., Oakland, Calif. 94603. Small quantities available from C. K. Chan, Richmond Field Station, University of California, Berkeley, Richmond, Calif., while supplies last. An alternative sand and corresponding calibration curve available from WES Soils Research Center, Vicksburg, Miss. 39180.

‡ Mulilis et al., op. cit.; Silver, op. cit.; and Silver et al., op cit.



PHYSICAL PROPERTIES

$\gamma_{d\ MAX}$ = 105.7 PCF e_{MIN} = 0.56

$\gamma_{d\ MIN}$ = 89.3 PCF e_{MAX} = 0.85

G_s = 2.65 D_{50} = 0.36 MM

Figure 11. Grain-size distribution and physical properties of Monterey No. 0 sand (SP)

pressure to be used is 14.50 psi. Sufficient back pressure to achieve a B value greater than 0.95 is required.

d. Testing Frequency. 1 Hz.

e. Test Results. Figure 9 presents the range in acceptable values for stress ratio versus number of cycles to initial liquefaction and 10 percent double amplitude strain.

8. POSSIBLE ERRORS. In addition to those described in paragraph 9, Appendix X, TRIAXIAL COMPRESSION TESTS, the following are possible errors that would cause inaccurate cyclic triaxial strength determinations :

a. Apparatus. (1) Loading wave form. Nonuniform, eccentric load wave forms may result from excessive piston friction, improper gain setting, or operation of the closed-loop servo valve. Insufficient air or hydraulic fluid at failure conditions will cause unacceptable load reduction. Misalignment between the loading piston and load actuator may also cause unacceptable loading wave forms.

(2) Electronic transducers and recording equipment. Improper calibration or sensitivity of the electronic transducers, incorrect balancing of amplifiers or zero settings, or improper range settings will result in inaccurate recording of actual loads, deformations, and pressures occurring during the test. It is also essential that the recorder response be rapid enough to follow all changes in the transducer output.

b. Specimen Preparation and Testing. (1) Specimen dimensions not measured precisely or density improperly calculated. A circumferential tape for measuring specimen diameter is recommended for obtaining precise measurements. Twice the thickness of the membrane must be subtracted for measurements of single membrane-encased specimens. An improperly calibrated burette will lead to incorrect volume change measurements during consolidation with resulting errors in specimen density computations.

(2) Percent undercompaction in lower specimen layers improper for achieving uniform density.

(3) Incomplete saturation resulting in low B values. A variety of problems can cause low B values: (a) use of insufficiently de-aired water may prevent dissolving of air in the specimen without resorting to extremely high back pressures; (b) incomplete de-airing or saturation of pore pressure transducer and drainage lines (can be avoided by applying a vacuum); and (c) system leaks due to punctured membrane, poor membrane sealing to cap and base, loose fittings, or improperly designed O-ring grooves (can be detected by using a bubble chamber while applying vacuum to the system).

(4) Incorrect application of consolidation stresses. Whenever the loading piston is fixed to the specimen cap, the static uplift load equal to the area of the piston rod multiplied by the chamber pressure must be accounted for when applying pressures, whether during back-pressure saturation, B-value checks, or consolidation.

(5) Prestraining specimens. By allowing the effective confining stress to vary, specimen strength can be greatly increased.†

(6) Scale factor for recorder traces not in agreement with actual data measurements. Reduction of data from recorder traces where incorrect scale factor, i.e., inches on recorder trace per pound (load), per inch (deformation), or per pounds per square inch (pressure), is used will result in data reduction error. The calibration steps should always be recorded on the recorder trace prior to and after testing.

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† Townsend, op. cit.

CYCLIC TRIAXIAL TEST (SPECIMEN DATA)			Date
Project			Boring No.
Sample No.	Depth El.	Test No.	Method of Specimen Preparation

Initial Condition of Specimen

Membrane thickness, in.	T	Top	Center	Bottom	Avg
Diameter, in.	D_o	Top	Center	Bottom	Avg
Height, in.	H_o	North	East	South	West	Avg

Area, sq in. = $0.7854\ D_o^2$	A_o		Dry density, lb/cu ft = $(W_s/V_o) \times 62.4$	γ_{do}	
Volume, cc = $16.39\ A_oH_o$	V_o		Relative density, %	D_{do}	
Initial weight soil, g	W_s		Specific gravity	G_s	

Condition of Specimen After Saturation and Consolidation

After Saturation			After Consolidation		
Change in height, in.	ΔH_{sat}		Change in height, in.	ΔH_c	
Height, in. = $H_o - \Delta H_{sat}$	H_{sat}		Height, in. = $H_{sat} - \Delta H_c$	H_c	
Area, sq in.	A_{sat}		Change in volume, cc	ΔV	
Volume, cc, = $16.39 A_{sat}H_{sat}$	V_{sat}		Volume, cc = $V_{sat} - \Delta V$	V_c	
			Area, sq in. = $0.061\ V_c/H_c$	A_c	
			Void ratio	e_c	
			Dry density, lb/cu ft = $(W_s/V_c) \times 62.4$	γ_{dc}	
			Relative density, %	D_{dc}	

Equations

$$D_{avg} = \frac{D_{top} + D_{center} + D_{bottom}}{3} - 2T$$

$$A_{sat} = \frac{A_o}{H_o}(H_o - 2\Delta H_{sat})$$

$$e_c = \frac{G_s \gamma_w}{\gamma_{dc}} - 1$$

After Test Results

Consolidation Pressure, $\bar{\sigma}_{3c}$, psi			Consolidation Stress Ratio, $K_c = \bar{\sigma}_{1c}/\bar{\sigma}_{3c}$				
Tare No.		Percent	N	P_c, lb	P_E, lb	$\pm\sigma_{dc} = \frac{P_c + P_E}{2A_c}$, psi	$\pm \frac{\sigma_{dc}}{2\sigma_{3c}}$
Tare and dry soil		$\epsilon_{da} = 5$					
Tare weight		$\epsilon_{da} = 10$					
Weight dry soil, g W_s		$\epsilon_{da} =$					
Remarks:		$\Delta u/\sigma_{2c} = 25$					
		$\Delta u/\sigma_{3c} = 50$					
		$\Delta u/\sigma_{3c} = 75$					
		$\Delta u/\sigma_{2c} = 100$					

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PLATE XA-1

CYCLIC TRIAXIAL TEST (SATURATION AND CONSOLIDATION WORKSHEET)			Date
Project			Boring No.
Sample No.	Depth El.	Test No.	Method of Specimen Preparation
Consolidation Pressure, $\bar{\sigma}_{3c}$, psi		Consolidation Stress Ratio, $K_c = \bar{\sigma}_{1c}/\bar{\sigma}_{3c}$	

Computation of Saturation and Consolidation Data

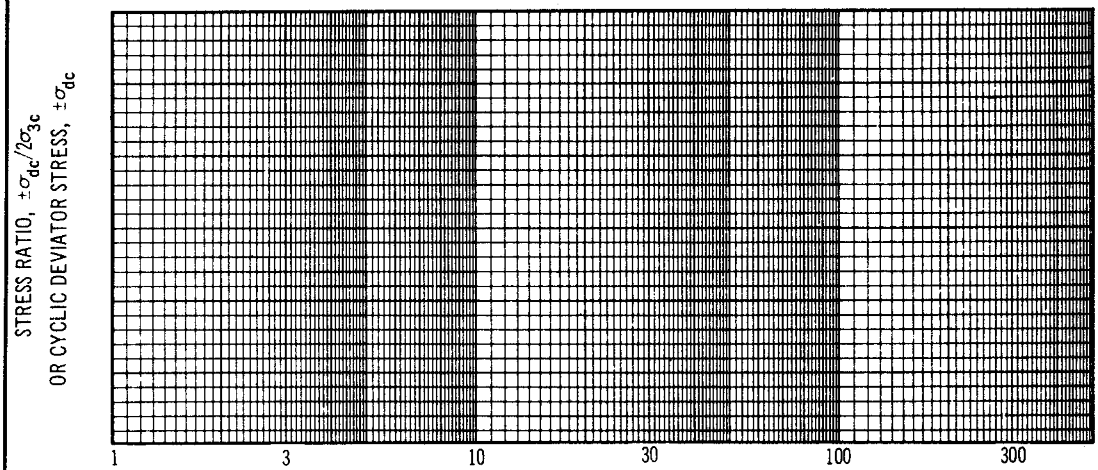
Step	Chamber Pressure σ_3 , psi	Uplift P_s lb	Back Pressure u , psi	Effective Confining Stress $\bar{\sigma}_{3c}$, psi	Axial Consolidation Load, $\bar{P}_s$, lb	Burette Reading cc	Dial Reading in.	Remarks

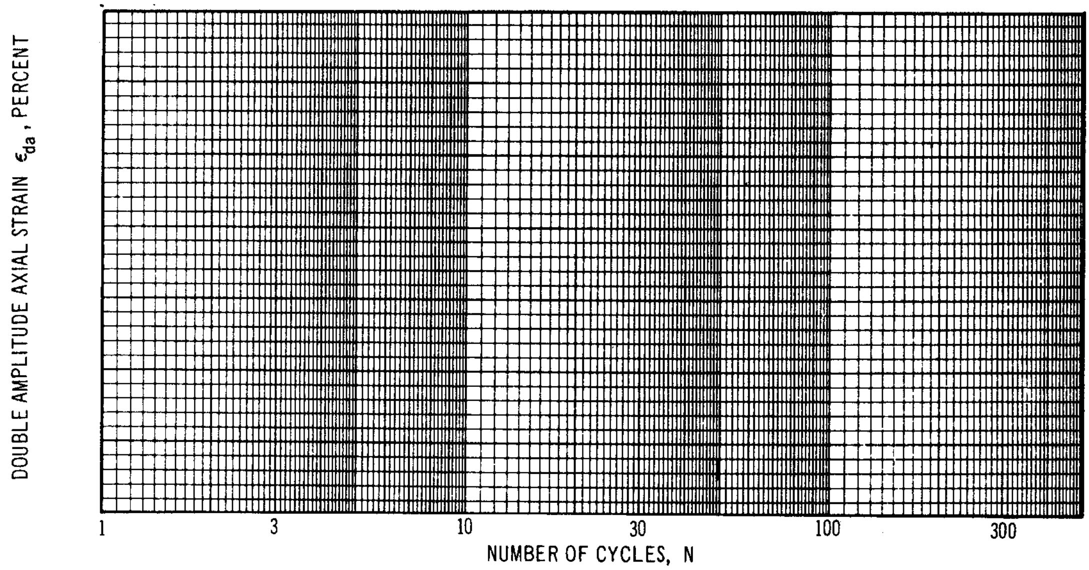
$P_s = \sigma_3 \times A_{rod}$ - wt of cap and piston $\qquad \bar{P}_s = P_s + A_{sat}(K_c - 1)\bar{\sigma}_{3c}$

Desired Loading Conditions

Desired stress ratio, $\pm\sigma_{dc}/2\bar{\sigma}_{3c}$ =	
Cyclic dev stress, $\pm\sigma_{dc} = 2\bar{\sigma}_{3c} \times SR$ =	psi
Cyclic load, ΔP_c or ΔP_E , $\pm\sigma_{dc} \times A_c$	lb

CYCLIC TRIAXIAL TEST REPORT		Date
Project		Boring No.
Sample No.	Method of Specimen Preparation	





SPECIMEN NO.	DENSITY	RELATIVE DENSITY	B	$\bar{\sigma}_{3c}$	CONSOLIDATION RATIO K_c	$\pm\sigma_{dc}$	$\pm\sigma_{dc}/2\bar{\sigma}_{3c}$	NUMBER OF CYCLES, N: PERCENT PORE PRESSURE INCREASE				NUMBER OF CYCLES, N: PERCENT STRAIN, ϵ_{da}		
								N_{25i}	N_{50i}	N_{75i}	N_i	N_5	N_{10}	N_{20}

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PLATE XA-2